



Enhancement of exergy efficiency in combustion systems using flameless mode



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ARTICLE INFO

Article history:

Received 7 April 2014

Accepted 10 June 2014

Available online 18 July 2014

Keywords:

Exergy efficiency
Conventional combustion
Flameless mode
Dilution
Preheated air

ABSTRACT

An exergitic-based analysis of methane (CH_4) conventional and flameless combustion in a lab-scale furnace is performed to determine the rate of pollutant formation and the effective potential of a given amount of fuel in the various combustion modes. The effects of inlet air temperature on exergy efficiency and pollutant formation of conventional combustion in various equivalence ratios are analyzed. The rate of exergy destruction in different conditions of flameless combustion (various equivalence ratios, oxygen concentration in the oxidizer and the effects of diluent) are computed using three-dimensional (3D) computational fluid dynamic (CFD). Fuel consumption reduction and exergy efficiency augmentation are the main positive consequences of using preheated air temperature in conventional combustion, however pollutants especially NO_x formation increases dramatically. Low and moderate temperature inside the chamber conducts the flameless combustion system to low level pollutant formation. Fuel consumption and exergy destruction reduce drastically in flameless mode in comparison with conventional combustion. Exergy efficiency of conventional and flameless mode is 75% and 88% respectively in stoichiometric combustion. When CO_2 is used for dilution of oxidizer, chemical exergy increases due to high CO_2 concentration in the combustion products and exergy efficiency reduces around 2% compared to dilution with nitrogen (N_2). Since the rate of irreversibilities in combustion systems is very high in combined heat and power (CHP) generation and other industries, application of flameless combustion could be effective in terms of pollutant formation mitigation and exergy efficiency augmentation.

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1. Introduction

Today around 80% of electricity of the world is provided by combustion process of which coal, natural gas and nuclear energy are the main sources of power generation by 45%, 20% and 15% respectively [1–3]. The chemical potential energy of the fuel is usually converted to the electricity by combustion phenomena in boiler steam turbine systems. Not only power generation but also development of industrial sectors is in debt of combustion systems. Steel factories, glass making, cement production, petroleum refining, food production are the main fossil fuel consumers through combustion systems in the world [4–7]. Therefore, combustion efficiency plays crucial role in heating-related energy savings. Heat is lost from combustors via various methods such as radiation losses and hot flue gas losses. Thus, it is vital to identify the energy wastage factors in the combustion system to optimize the combustion operation. It has been pointed out that if the temperature of exhaust gases in a

boiler is about 550 K, around 30% of the boiler's energy is wasted. Hence, substantial part of energy could be returned by the heat recovery from flue gases [8]. Although the first law of thermodynamics (FLT) is applied to analyze the energy consumption, the quality aspect of energy is not taken into consideration. Therefore, exergy analyses based on second law of thermodynamic (SLT) should be done to determine the effective work potential of a given amount of energy at reference state. Energy and exergitic analyses have been performed for various industrial systems in different countries [9–13]. In addition, exergy-based analysis is usually done to evaluate the performance of thermochemical or thermal systems [14,15]. Exergy expresses the right efficiency of the engineering systems through linkage between the physical, engineering and environment aspects. Thus, exergy computation can provide a deeper insight into the system and new projections for process improvement could be feasible [16]. Consequently, both energy and exergy analyses of a process is vital to optimize and improve the performance of the system through taking appropriate energy strategies [17,18]. Furthermore, exergy analysis plays crucial role for global environmental, national pollution reduction, energy planning, resource optimization and regional.

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Nomenclature

τ_{ij}	stress tensor	C_p	specific heat capacity
q_i	heat flux	S_{out}	entropy of exhaust
\bar{S}_k	species mole flux per unit area	S_r	reference entropy
J_{ki}	chemical potential	P_{out}	outlet pressure
x_k	partial mole entropy of k th species	P_r	reference pressure
\dot{w}_c	reaction rate of the c th chemical reaction	ex_{ch}^k	standard molar chemical exergy (kJ/mol)
γ''_{kr}	stoichiometric coefficient on reactant side	P_{wv}	pressure of water vapor
γ'_{kr}	stoichiometric coefficient on product side	T_{wv}	water vapor temperature
$ex_{ph,out}$	physical exergy at outlet	P_s	partial pressure
$ex_{ch,out}$	chemical exergy at outlet	n_{wv}	mole of water vapor
$ex_{in,O}$	inlet exergy of oxidizer	x_{dry}	mole of dry products
h_{out}	enthalpy at outlet	$\dot{E}x_Q$	exergy destruction
T_r	reference temperature	\dot{m}	mass flow rate
T_{out}	exhaust temperature		

Due to importance of combustion systems in the industrialization, some fundamental investigations have been done to improve the efficiency of combustion process. Therefore study about performance of gaseous fuel in the combustion systems, heat transfer of combustor, effects of excess air and exhaust gas recirculation on the combustion stability have been more highlighted. Furthermore, depletion of fossil fuel resources and stringent environmental laws have conducted the combustion studies to find efficient and clean combustion technologies [19]. Flameless combustion known as Moderate and Low oxygen Dilution (MILD) combustion [20], Low NO_x Emission Injection or Colorless Distributed Combustion (CDC) [21], High Temperature Air Combustion (HiTAC) [22] and Flameless Oxidation (FLOX) [23] is a new combustion method for industrial chambers has been recently developed to reduce emissions and simultaneously to generate high efficiency in the combustion process. Flameless combustion has been utilized in steel making, cement industries and glass making factories [24,25], industrial boilers [26], gas turbines [27] and such industries that an uniform temperature distribution within the furnace is required [25]. In gaseous fuel flameless combustion, gas and highly diluted and preheated air react at the temperatures over the auto-ignition temperature of the fuel. In this circumstance, flame could not be stable and lifts off [28]. Flameless combustion regime could be sustained when diluted air injected into the chamber at extremely high velocity [29], thus low amount of oxygen concentration and high Reynolds number of oxidizer disappears the flame [30]. Flameless combustion of various gaseous fuel such as methane, propane, biogas and natural gas has been investigated [31–36]. In the experimental investigation performed by Hosseini et al. [37], the thermal efficiency of biogas conventional and flameless combustion in a lab-scaled furnace was reported 32% and 53% respectively. Colarado et al. [38] pointed out that the efficiency of natural gas flameless combustion is 2% higher than biogas. Low NO_x formation and fuel consumption reduction are the main characteristics of gaseous fuel flameless combustion technology which have been discussed in various literatures [37,39,40]. Although combustion characteristics of various fuel flameless mode have been developed in terms of energy saving and pollutant reduction experimentally and numerically, the SLT-based analyses of flameless combustion system has not been taken into account. In this study, exergitic-based analysis of conventional and flameless combustion in a lab-scale furnace is investigated and the effects of various parameters such as equivalence ratio, dilution and the temperature of preheated oxidizer on the exergy destruction of the combustion system are analyzed.

Heat transfer through chamber walls is responsible for a part of energy loss in the combustion furnaces. Thus, combustors are

usually insulated to minimize heat dissipation to the environment. Since maintaining the heat inside the furnace is crucial in the sustainability of flameless mode, high-qualified refractory such as ceramic should be installed inside the chamber. Consequently, heat loss from flameless combustors is very low [41]. In theoretical study, work involvement of the adiabatic chambers, potential and kinetic energy of the air and gaseous fuel streams are usually neglected.

1.1. Exergy of gaseous fuel combustion

Exergy analysis of various models of conventional combustion such as premixed and non-premixed, turbulent jet flames as well as laminar flame have been developed by different researchers up to now. The related investigations were done by numerical approach of the conservation equations to calculate the rate of entropy generation of combustion process. Stanciu et al. [42] pointed out that in laminar non-premixed flame when pressure is constant, an uncoupled irreversibility is created due to mass diffusion, viscous dissipation, chemical reactants and heat conduction. Local entropy generation in a laminar non-premixed flame was analyzed by Nishida et al. [43]. Temperature distribution inside the chamber as well as the radial mole fraction of species and the rate of local entropy generation for irreversible processes at a single axial height were presented. It was concluded that the contribution of thermal conduction in entropy generation is more important than the contribution of chemical reactions. A numerical investigation was performed by Datta et al. [44] to analyze the entropy generation of laminar non-premixed flame of methane/air. The chemical reaction was considered single step and Lewis number was unity. It was found that the effect of viscous dissipation could be neglected and the entropy generation was attributed to mass diffusion, chemical reaction and thermal diffusion. Entropy generation inside the combustion furnace has been attributed to the non-equilibrium circumstances because the exchange of energy, momentum and mass of various species within the solid boundaries and the fluid. In the other word, chemical reactant, irreversible nature of viscous effects, mass diffusion and heat transfer between fluid and solid boundaries, body force effects as well as coupling effects between heat and mass transfer are the main causes of entropy generation in the combustion systems. Therefore, the local entropy generation is derived from Eq. (1) [45].

$$\dot{S}_{gen} = \frac{\tau_{ij}(\frac{\partial u_i}{\partial x_j})}{T} - \frac{\dot{q}_i}{T^2} \frac{\partial T}{\partial x_i} - \frac{\sum_{k=1}^K \dot{J}_{k1}(\frac{\partial x_k}{\partial x_i})}{T} - \frac{\sum_{k=1}^K \bar{S}_k \dot{J}_{k1}(\frac{\partial T}{\partial x_i})}{T} + \frac{\sum_{k=1}^K \dot{J}_{ki} f_{ki}}{T} - \frac{\sum_{c=1}^R \dot{w}_c \sum_{k=1}^K (\gamma''_{kr} - \gamma'_{kr}) x_k}{T} \quad (1)$$

In Eq. (1), the first term in the right hand side is from the gaseous fuel friction, the second and third terms are due to heat and mass transfer respectively and the fourth term is their coupling result, the fifth term is from the body force effects and the sixth term is due to the chemical reactions.

2. Flameless achievement

In order to obtain flameless combustion, the system should be run in the conventional regime to preheat the furnace and increase the temperature within the chamber more than the auto-ignition of the fuel. After transient step, flameless mode is started when high temperature diluted oxidizer injected into the chamber at high velocity and flame front is disappeared. In this circumstance, audible and visible flame is paled and the reaction zone spreads to the downstream region of the chamber, hot spots are eliminated, uniform temperature is appeared inside the furnace and NO_x formation reduces. In the flameless combustion regime, since flame is not constituted, the peak temperature and consequently the mean temperature of the furnace is lower than conventional combustion [46].

2.1. Numerical setting

In this study, the lab-scaled flameless furnace system presented in ref [37] is the basic model for computations. The 3D simulation of this chamber was performed with ANSYS 14 using ANSYS Modeler to design the chamber and ANSYS Meshing [47] to mesh the furnace by Ref. [48] and the numerical setting and governing equations were explained for biogas flameless combustion. Fig. 1 displays the schematic of the studied chamber.

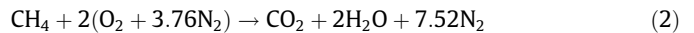
Due to the symmetry of the combustor, in order to decrease the number of iterations and consequently to reduce computational time, just an eighth part of the furnace is applied for meshing. Same setting has been utilized for CH_4 flameless combustion in this project. The behavior between mixing and reaction in a combustion system is characterized by Damköhler (D_a) number, which is defined as the ratio of the flow time-scale to the chemical time-scale. Since D_a number is more than one, specious transport, methane-air-2step are set for mixture modeling and eddy dissipation model (EDM) is adjusted for turbulence chemistry interaction [47]. The concentration of oxygen in the oxidizer stream is set 21% by volume for CH_4 conventional combustion and 7% by volume in the flameless mode and dilution is done by nitrogen (N_2). In order to study the effects of oxidizer dilution on the exergy efficiency, flameless combustion by 5% and 10% oxygen concentration is simulated too. A part from N_2 , oxidizer is also diluted by CO_2 to study the effects of various diluents on the exergy efficiency of

flameless mode. The inlet temperature of CH_4 and oxidizer are 300 K and in order to study the various aspects of traditional combustion, the effects of preheated oxidizer ($T_{\text{inlet,air}} = 500, 700, 900 \text{ K}$) as well as equivalence ratio ($\phi = 0.6, 0.8, 1, 1.2$) are simulated. Indeed, the characteristics of flameless combustion in terms of exergy destruction is investigated in the aforementioned equivalence ratios when ($T_{\text{inlet,air}} = 900 \text{ K}$). Preheated oxidizer provides the required enthalpy for CH_4 flameless combustion. The summaries of inlet oxidizer boundary condition and fuel inlet, wall and pressure outlet boundary condition have been presented in Tables 1 and 2 respectively. In addition, Table 3 illustrate the general setting of simulation.

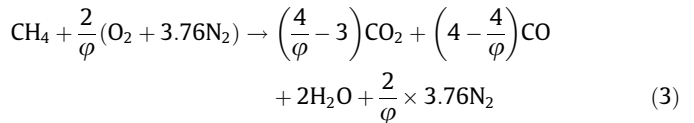
2.2. Theoretical assumptions

Obviously, the primary way of exergy destruction minimization in a combustion system is irreversibility reduction in chemical reactions and heat conduction through appropriate control of physical processes. In the calculation of combustion system exergy, kinetic and potential exergy are neglected and just physical and chemical exergy are taken into consideration. Physical exergy of a system is equal to the maximum amount of work than can be achieved from the system when the temperature and pressure of the system are changed to the temperature and pressure of the reference environment [49]. Chemical exergy is very important in industrial systems which chemical energy converted to the other kinds of energy like combined heat and power (CHP) generation from combustion process. Chemical exergy is defined as the maximum work, which can be extracted from a system in heat transfer and exchange the system with the reference environment when the system is changed from the reference environment state to the dead state [49,50]. Since in combustion systems, a considerable part of exergy is destructed through chemical exergy, it should be considered in the various computation modes.

In complete stoichiometric combustion of methane, when sufficient air is available, the chemical reaction could be written as Eq. (2).



In insufficient air circumstances, oxygen of air reacts with hydrogen of the fuel to constitute the water. Depend on the availability of oxygen; O_2 converts carbon to carbon monoxide (CO) or carbon dioxide (CO_2). Thus with respect to the equivalence ratio, Eq. (3) could be a criterion in the computations.



The specific physical exergy at the outlet of combustor is calculated from Eq. (4).

$$\begin{aligned} ex_{ph,out} &= (h_{out} - h_r) - T_r(S_{out} - S_r) \\ &= C_p(T_{out} - T_r) - T_r \left[C_p \ln \left(\frac{T_{out}}{T_r} \right) - R \ln \left(\frac{P_{out}}{P_r} \right) \right] \end{aligned} \quad (4)$$

Since the pressure drop through combustion furnace is neglected $P_{outlet} = P_{inlet}$. Depend to the conventional or flameless mode of combustion C_p is considered constant.

The specific chemical exergy at the outlet of combustor is computed from Eq. (5).

$$ex_{ch,out} = \sum x_k ex_{ch}^k + RT_r \sum x_k \ln x_k \quad (5)$$

where x_k is mole fraction of specious k in the outlet and ex_{ch}^k is standard molar chemical exergy (kJ/mol) [16].

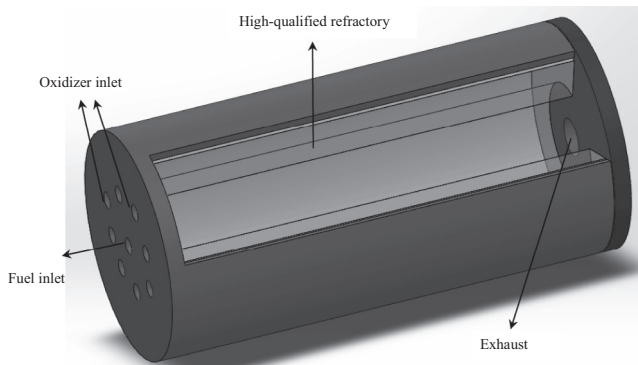


Fig. 1. The schematic of flameless chamber.

Table 1
Boundary conditions of oxidizer inlet.

Oxidizer inlet	
Temperature	Uniform
Flameless combustion	900 K
Conventional mode	300 K, 500 K, 700 K, 900 K
Gauge Pressure	0
Hydraulic diameter	5 mm
Velocity	
Flameless mode	90 m/s
Conventional mode	30 m/s
Turbulent intensity	10
Oxygen concentration	
Flameless combustion	5%, 7%, 10%
Traditional combustion	21%
Density	
Flameless mode ($T_{inlet} = 900\text{K}$)	
5% Oxygen concentration	0.382 g/l
7% Oxygen concentration	0.383 g/l
10% Oxygen concentration	0.3847 g/l
Conventional combustion (21% Oxygen concentration)	
$T_{inlet} = 300\text{ K}$	1.177 g/l
$T_{inlet} = 500\text{ K}$	0.7063 g/l
$T_{inlet} = 700\text{ K}$	0.5046 g/l
$T_{inlet} = 900\text{ K}$	0.3925 g/l
Mass flow rate	Various based on the inlet temperature and oxygen concentration

Table 2
Boundary condition of fuel inlet, wall and pressure outlet.

Fuel inlet	Temperature	Uniform, 300 K
	Gauge pressure	0
	Hydraulic diameter	5 mm
	Velocity	21 m/s
	Turbulent intensity	10
	Fuel	CH ₄
	Density	0.66 g/l
Wall	Wall slip	Non-slip
	Material	Steel
	Thermal condition	Mixed
	Heat transfer convection	5 w/m ² K
Pressure outlet	Hydraulic diameter	50 mm
	Gauge pressure	0
	Turbulent intensity	5

Table 3
Settings of simulation.

Viscous model	$k-\epsilon$ Standard
Radiation model	Discrete ordinate (DO)
Combustion model	Species transport
Mixture properties	Methane–air 2step
Turbulence chemistry interaction	EDM
Reaction	Volumetric
NO _x	Thermal NO _x Prompt NO _x

When gaseous product is cooled at the constant pressure below the dew point temperature, condensation would occur. Thus, the exact specific chemical exergy should be calculated with respect to the liquid water constitution. The partial pressure of the water vapor is calculated by Eq. (6).

$$P_{wv} = x_{wv} P_r \quad (6)$$

where P_r is considered 1.0135 bar.

If the corresponding temperature of the water vapor (T_{wv}) is more than the temperature of the reference (300 K), liquid water is formed based on Eq. (7).

$$P_s = \frac{n_{wv}}{x_{dry} + n_{wv}} \quad (7)$$

where P_s is partial pressure of water vapor at $T = 300\text{ K}$ (considered 0.0316) and x_{dry} is the summation of mole fraction of all products except water. The modified chemical exergy is calculated based on the Dincer et al. [16] method. The modified chemical exergy is constituted of two terms; the first term is the specific chemical exergy (from Eq. (5)) multiplied by the percentage of dry combustion gases (x_{dry}) and the second term is the product of the specific chemical exergy of liquid water and the molar fraction of liquid water due to the condensation. By calculation of physical and chemical exergy, the total exergy of the exhaust gases at the outlet of the chamber would be computable.

$$ex_{out} = ex_{ch,out} + ex_{ph,out} \quad (8)$$

The total mass flow rate of flue gases is computed with respect to the mass flow rate of fuel and oxidizer. Based on ref [51], the exergy of fuel is set based on the Eq. (9).

$$ex_{inlet,fuel} = \varphi \times LHV \quad (9)$$

Lower heating value of methane is 500,016 kJ/kg and $\varphi_{CH_4} = 1.06$.

Moreover $ex_{inlet, oxidizer}$ is calculated through Eq. (10).

$$ex_{in,o} = C_p(T_{in} - T_r) - T_r \left[C_p \ln \left(\frac{T_{in}}{T_r} \right) - R \ln \left(\frac{P_{in}}{P_r} \right) \right] \quad (10)$$

By applying the general exergy balance for the combustor, the rate of exergy destruction is calculated.

$$\dot{Ex}_Q + \sum_{inlet} \dot{m}_{inlet} ex_{inlet} = \sum_{outlet} \dot{m}_{outlet} ex_{out} + \dot{Ex}_w + \dot{Ex}_D \quad (11)$$

Hence

$$\dot{Ex}_D = \dot{Q}_{cv} \left(1 - \frac{T_r}{T_{out}} \right) + \dot{m}_{inlet, oxidizer} ex_{in,o} + \dot{m}_f ex_f - (\dot{m}_{in,o} + \dot{m}_f) ex_{out} \quad (12)$$

3. Results and discussion

Comparison between numerical and experimental results of conventional and flameless combustion regimes confirms that the numerical solution has about 5% over prediction compared to the experimental records. These discrepancies could be attributed to the errors related to the measurement equipment and adverse factors. Therefore, exergy analysis of various combustion modes based on numerical approach could be reliable. Fig. 2 illustrates the effects of inlet air temperature on the exergy destruction in various equivalence ratios. The maximum exergy efficiency could be obtained in stoichiometric combustion ($\varphi = 1$). Also the rate of exergy destruction reduces when the temperature of combustion air increases.

Fig. 2 shows that the total exergy loss is minimized with the increase in inlet air temperature. These variations could be attributed to the reduction of thermal diffusion as well as chemical reaction contributions. The stability of the preheated air conventional combustion could be ensured due to the increases of flame temperature and consequently reduction of the temperature gradient resulting diffusive heat flux mitigation. The chemical reactions that are occurred in the high temperature conventional flame reduce their contribution to the exergy loss. Fig. 3 demonstrates fuel consumption and NO_x formation in preheated-air methane

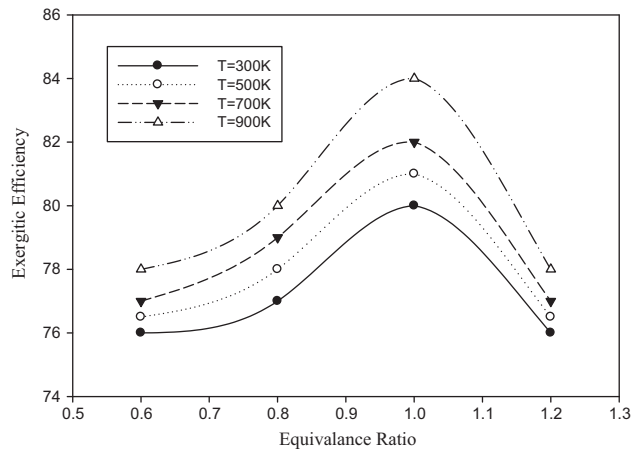
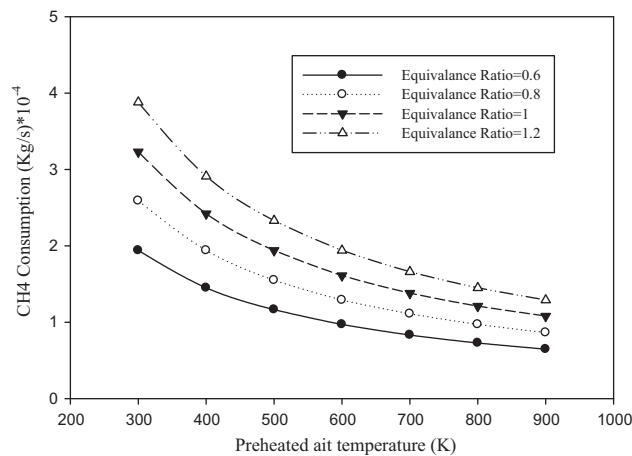
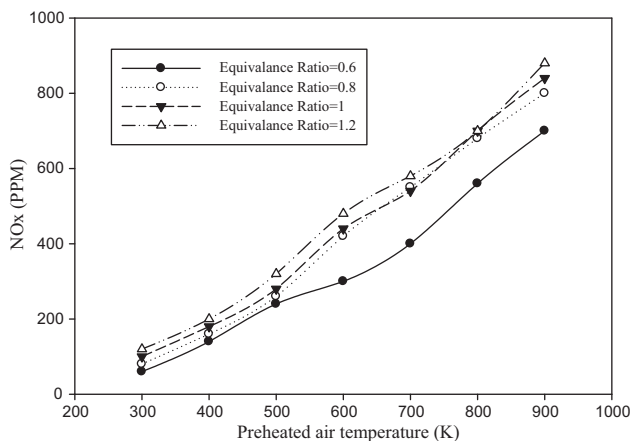


Fig. 2. Effects of inlet air temperature on the exergy efficiency in conventional combustion with respect to various equivalence ratios.

conventional combustion. From this Figure, it can be seen that the rate of NO_x formation increases exponentially when the temperature of oxidizer increases. This fact is attributed to NO_x formation via thermal NO_x mechanism [52]. Although fuel consumption reduction is one of the main advantages of this method (Fig. 3A),



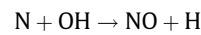
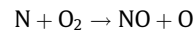
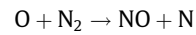
(A)



(B)

Fig. 3. (A) CH_4 consumption and (B) NO_x formation in preheated-air conventional combustion.

due to extremely high NO_x formation (Fig. 3B), this method of combustion is not recommended. NO_x formation reduction in the combustion processes is essential to control acid rain, global warming, smog, ozone depletion and greenhouse gases effects. NO_x is constituted due to the reaction of nitrogen (N_2) and oxygen within a locally high temperature region. The environment can be endangered by increasing NO_x . At extremely high temperatures, N_2 and O_2 react through Zeldovich chemical mechanisms (Eq. (13)).



(13)

The reaction rate constants of the reactions are selected from ref [53]. Thermal NO_x formation is quickened at high temperatures and the rate of generation augments quickly with increasing temperature.

Som et al. [54] reported that the high temperature gradients in the combustion zone is the main source of combustion irreversibilities. One of the most important priorities of flameless combustion is the uniformity of temperature inside the chamber. The mean temperature within the chamber is lower than conventional mode and hot spots are eliminated. Thus, not only NO_x formation reduction is predicted in flameless mode, but also exergy destruction reduction is predictable. Fig. 4 shows the volumetric of temperature distribution inside the chamber in conventional and flameless combustion ($T = 300 \text{ K}$, Oxygen concentration = 7%).

Compared to the conventional combustion, the rate of fuel consumption decreases dramatically in flameless mode (for instance in the stoichiometric combustion fuel consumption in conventional combustion and flameless mode were recorded 0.322 g/s and 0.191 g/s respectively). Furthermore, NO_x formation reduces due to hot spot elimination and thermal NO_x suppression. From observations, it can be construed that moderate temperature inside the flameless chamber is the main cause of thermal NO_x suppression and consequently low NO_x formation. Depend on the combustion regime, equivalence ratio and oxidizer temperature, the mole fraction of produced gaseous fuel is various. Fig. 5 demonstrates the mole fraction of the most important products of CH_4 combustion in different states based on the computational results.

The rate of N_2 in the exhaust gases is higher in the flameless mode compared to the conventional combustion because combustion air is diluted by nitrogen. This fact implies that O_2 concentration in the exhaust is gases is very low in the flameless mode. Fig. 6 shows the concentration of various species of combustion reactants like CH_4 and O_2 , and combustion products such as CO , CO_2 and H_2O in both conventional and flameless combustion. The species distribution is the result of chemical reaction as well as mass transport process in multicomponent circumstances.

In both combustion modes, CH_4 consumed rapidly at the burner zone and its concentration decreases drastically. Therefore, CH_4 species could be observed only inside the flame region in conventional combustion and near burner in the flameless mode (Fig. 6A). The co-flow oxidizer jet transports the peripheral side of the flame in the traditional combustion. Oxygen is consumed at the flame surface and its trace is located at the flame region in conventional mode. However, the low oxygen concentration in flameless region consumed rapidly near the burner zone (Fig. 6B). In conventional combustion, CO is formed inside the flame and it could be found inside surface of the flame due to the shortage of oxygen. The lack of oxygen inside the flame is responsible for CO formation in this region. CO species that comes outside of the flame front surface are consumed readily with oxygen. In flameless combustion mode, CO formation is developed throughout the furnace due to low oxygen concentration (Fig. 6C). In CH_4 two-step combustion model following chemical reactions are occurred [55]:

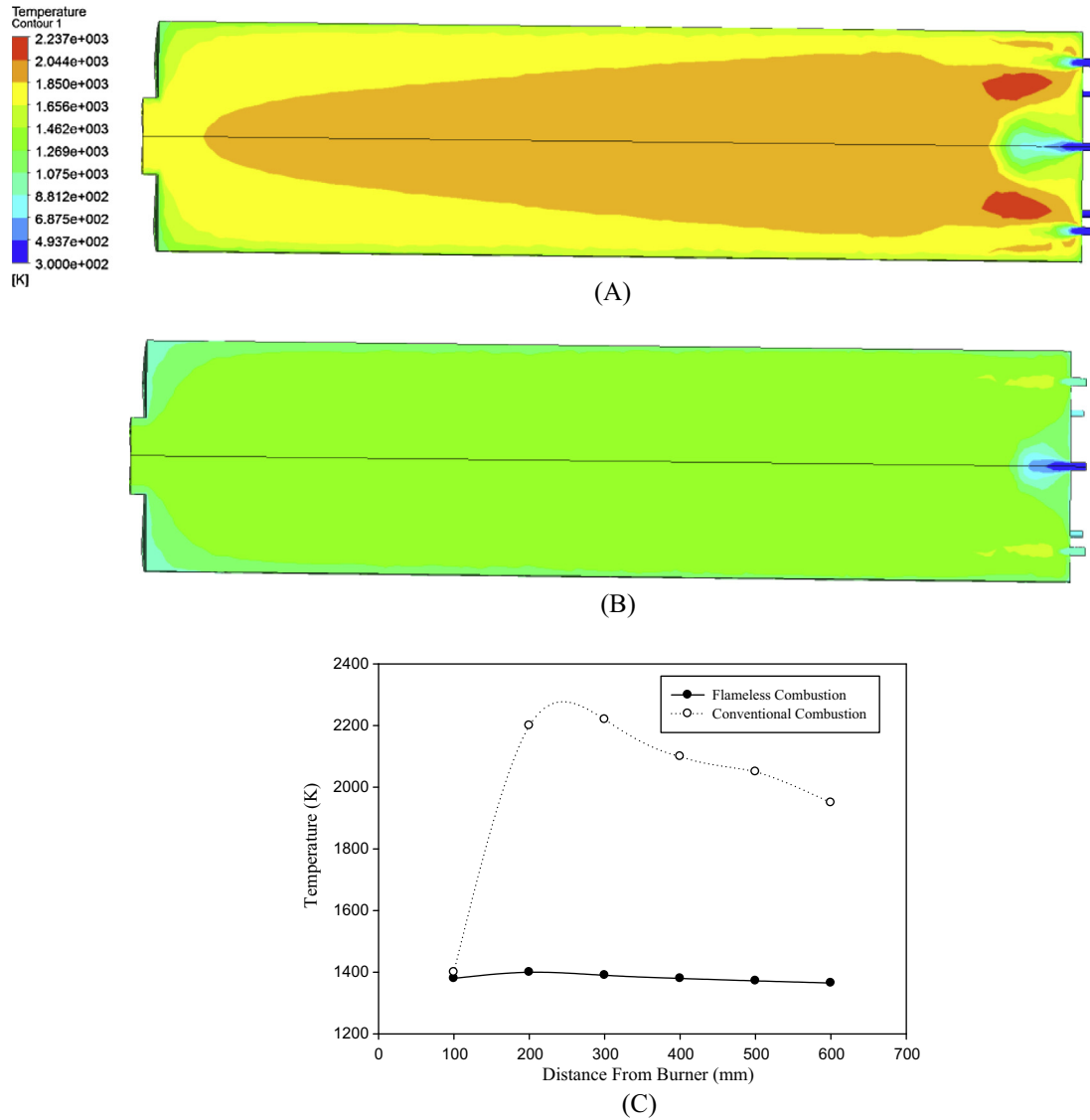


Fig. 4. Temperature distribution inside the chamber (A) conventional combustion, (B) flameless combustion, and (C) temperature distribution in the centerline of the furnace.

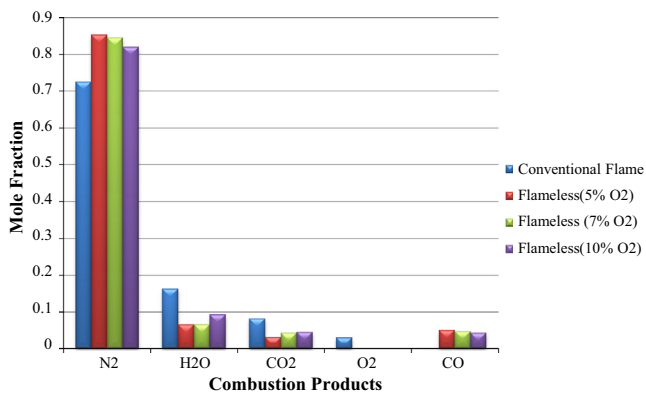


Fig. 5. Mole fraction of combustion products in the various combustion modes.



In reaction (14), CO and H₂O are constituted; while in the reaction (15), CO is converted to CO₂ in the presence of O₂. Since low oxygen concentration is associated with the flameless mode, CO could not be converted to CO₂. Thus, the rate of CO formation in the flameless mode is extended throughout the furnace. CO₂ and H₂O are constituted in the flame front of conventional mode and based on the diffusive rates they are transported in all directions. The transport of H₂O and CO₂ species in the flameless mode continues downstream until the exit plane is reached (Fig. 6D and E). In the traditional combustion, the major mass transport takes place in the flame zone due to the sudden mitigation of reactants concentration and huge amount of combustion products generation. Therefore, combustion irreversibility and consequently entropy generation is appeared due to heat and mass transport processes. The rate of irreversibilities are maximized at locations where the field gradient are high. Fig. 7 depicts the contours of local volumetric entropy generation in both studied combustion modes.

From this figure, it can be construed that the entropy generation occurs within the flame front in conventional mode. Since the rate of entropy generation is higher near the base of the flame, it can be

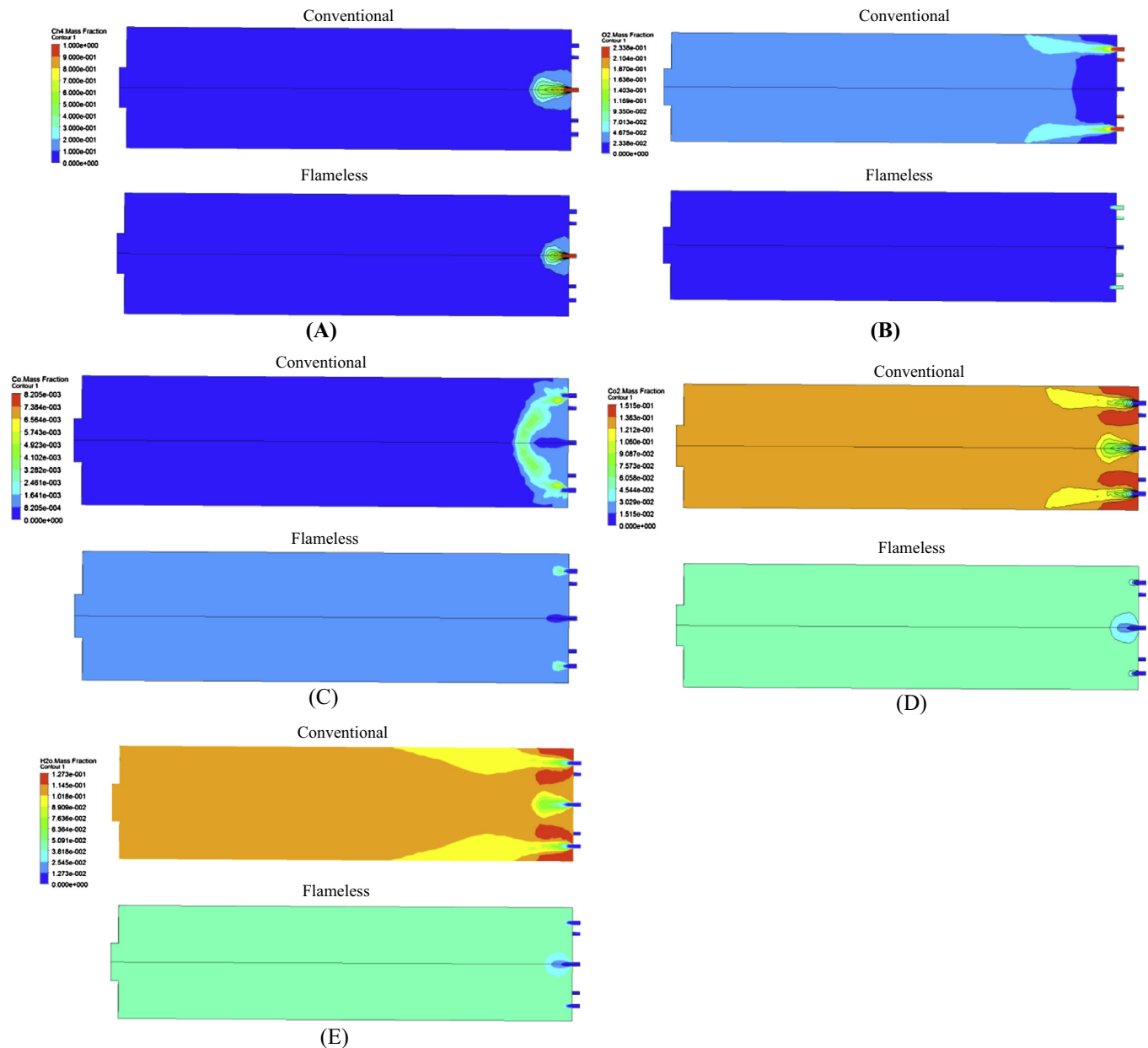


Fig. 6. Concentration of various species inside the furnace (A) CH₄, (B) O₂, (C) CO, (D) CO₂, and (E) H₂O.

concluded that the flame is more intense near the burner (Fig. 4A shows this fact). In the contrary, at the tip of the conventional flame, the flame is weak and the entropy generation rate is low. CH₄ concentration is more near the burner and thus higher diffusion rate of fuel towards the flame front is observed. In the further locations, CH₄ concentration reduces due to fuel consumption and the intensity of the flame mitigates. In the flameless combustion regime, entropy generation is weaker due to lower concentration of CH₄ and high momentum of hot co-flow oxidizer. In addition, entropy generation via thermal diffusion in conventional combustion is stronger than flameless mode due to very high temperature gradient in front of the conventional burner. Furthermore, in conventional combustion, high temperature gases constitute a thermal stratification near the core and the fresh inlet air forms a zone near the walls and around the flame periphery. Thus an annular zone between the walls and the core is generated which the rapid

temperature reduction causes high rates of heat transfer. Due to this high temperature gradient, high diffusion of heat is developed throughout the chamber and generates entropy. With respect to the calculation of liquid water chemical exergy of the combustor is shown in Fig. 8.

From this Figure, it can be seen that chemical exergy of flameless combustion is lower than conventional mode when dilution of oxidizer is done by N₂. The very high chemical exergy of CO₂-based diluted oxidizer flameless mode could be attributed to the high concentration of CO₂ at the combustion products. The mole fraction of CO₂ at the flameless combustion products was recorded 0.0311 and 0.164 for N₂ and CO₂ oxidizer dilution methods respectively. Since the standard chemical exergy of CO₂ is extremely higher than other products, very high chemical exergy in CO₂-based diluted flameless combustion is reasonable. Although chemical exergy of CO₂-based dilution method of flameless mode

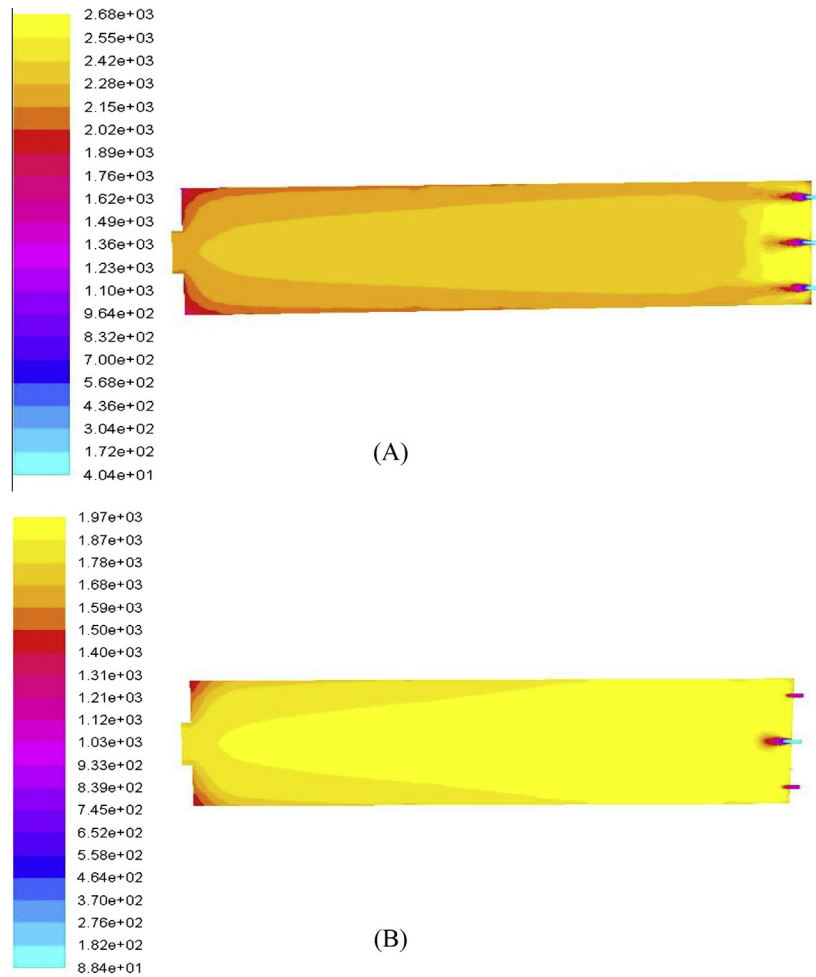


Fig. 7. Local volumetric entropy generation in (A) conventional and (B) flameless combustion.

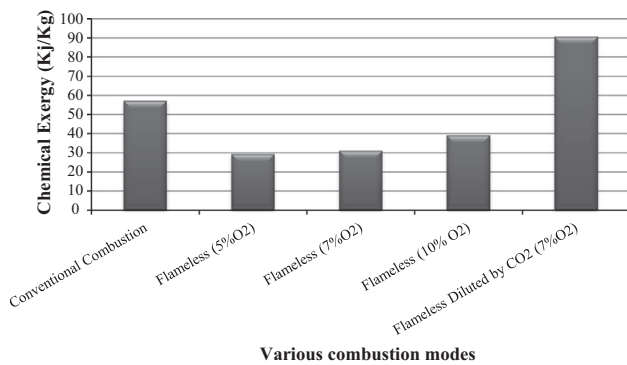


Fig. 8. Chemical exergy of various combustion modes.

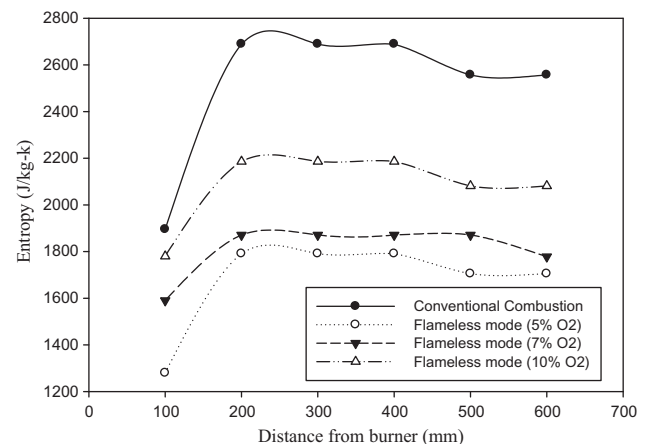


Fig. 9. Entropy generation in the centerline of the chamber.

is very high, the exergy efficiency of this method was computed 88% which is higher than conventional combustion by around 75%.

Figs. 9 and 10 depict the rate of entropy generation within the furnace and exergy efficiency of various combustion modes respectively.

The exergy of oxidizer inlet in flameless mode is higher than conventional mode due to high temperatures of oxidizer, however

in order to achieve a certain combustion condition (for example stoichiometric combustion) the rate of fuel inlet decrease drastically. Since the rate of total fuel and air inlet reduces dramatically in flameless mode, exergy destruction decreases and the rate of total exergy efficiency enhances.

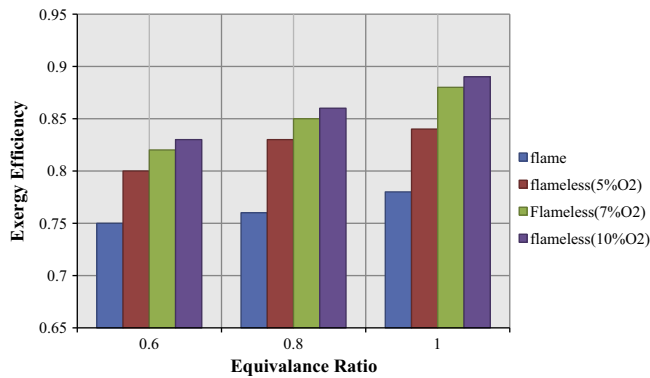


Fig. 10. Exergitic efficiency of the chamber.

4. Conclusion

Since the rate of exergy destruction in combustors is very high in industries especially in CHP generation, study on various aspects of combustion has been highlighted. Irreversibilities of combustion phenomena are attributed to the high temperature gradients inside the chamber. Thus since the temperature of flameless combustion is moderate and lower than conventional mode, application of flameless combustion could be effective in terms of pollutant formation mitigation and exergy efficiency augmentation. In the flameless combustion, hot spots are eliminated therefore; low NO_x emission as well as low exergy destruction could be achieved. In the preheated air conventional combustion, although exergy efficiency is improved, pollutants especially NO_x formation increases drastically. Fuel consumption as well as irreversibilities reduce in flameless mode. Maximum exergy efficiency was recorded in stoichiometric combustion circumstances. Exergy efficiency of flameless combustion was around 13% higher than conventional mode in stoichiometric combustion. When CO₂ is used for dilution of oxidizer, chemical exergy increases due to high CO₂ concentration in the combustion products and exergy efficiency reduces around 2% compared to dilution with nitrogen (N₂).

References

- [1] Hosseini SE, Wahid MA. Pollutant in palm oil production process. *J Air Waste Manage Assoc* 2013. <http://dx.doi.org/10.1080/10962247.2013.873092>.
- [2] Saidur R, Ahamed JU, Masjuki HH. Energy, exergy and economic analysis of industrial boilers. *Energy Policy* 2010;38:2188–97.
- [3] Hosseini SE, Andwari AM, Wahid MA, Bagheri G. A review on green energy potentials in Iran. *Renew Sustain Energy Rev* 2013;27:533–45.
- [4] Kaviri AG, Jaafar MNM, Lazim TM. Modeling and multi-objective exergy based optimization of a combined cycle power plant using a genetic algorithm. *Energy Convers Manage* 2012;58:94–103.
- [5] Kaviri AG, Jaafar MNM, Lazim TM, Barzegaravval H. Exergoenvironmental optimization of Heat Recovery Steam Generators in combined cycle power plant through energy and exergy analysis. *Energy Convers Manage* 2013;67:27–33.
- [6] Renó MLG, Torres FM, da Silva RJ, Santos JCS, Melo M de LNM. Exergy analyses in cement production applying waste fuel and mineralizer. *Energy Convers Manage* 2013;75:98–104.
- [7] Kaşka Ö. Energy and exergy analysis of an organic Rankine for power generation from waste heat recovery in steel industry. *Energy Convers Manage* 2014;77:108–17.
- [8] Jayamaha L. Energy-efficient building systems: green strategies for operation and maintenance: green strategies for operation and maintenance; 2006.
- [9] Ziya SÖÇÜTM. A research on exergy consumption and potential of total CO₂ emission in the Turkish cement sector. *Energy Convers Manage* 2012;56:37–45.
- [10] Zarifi F, Mahlia TMI, Motasemi F, Shekarchian M, Moghavvemi M. Current and future energy and exergy efficiencies in the Iran's transportation sector. *Energy Convers Manage* 2013;74:24–34.
- [11] Rivero R. Application of the exergy concept in the petroleum refining and petrochemical industry. *Energy Convers Manage* 2002;43:1199–220.
- [12] Açıkkalp E, Aras H, Hepbasli A. Advanced exergy analysis of an electricity-generating facility using natural gas. *Energy Convers Manage* 2014;82:146–53.
- [13] Mozes E, Cornelissen RL, Hirs GG, Boom RM. Exergy analysis of the conventional textile washing process. *Energy Convers Manage* 1998;39:1835–43.
- [14] Ray TK, Ganguly R, Gupta A. Optimal control strategy for minimization of exergy destruction in boiler superheater. *Energy Convers Manage* 2013;66:234–45.
- [15] Neveu P, Tescari S, Aussel D, Mazet N. Combined constructal and exergy optimization of thermochemical reactors for high temperature heat storage. *Energy Convers Manage* 2013;71:186–98.
- [16] Dincer I, Rosen MA. EXERGY: energy, environment and sustainable development (Google eBook). Newnes; 2012.
- [17] Kanoglu M, Dincer I, Rosen MA. Understanding energy and exergy efficiencies for improved energy management in power plants. *Energy Policy* 2007;35:3967–78.
- [18] Cassetti G, Colombo E. Minimization of local impact of energy systems through exergy analysis. *Energy Convers Manage* 2013;76:874–82.
- [19] Hosseini SE, Wahid MA, Aghili N. The scenario of greenhouse gases reduction in Malaysia. *Renew Sustain Energy Rev* 2013;28:400–9.
- [20] Özdemir IB, Peters N. Characteristics of the reaction zone in a combustor operating at mild combustion. *Exp Fluids* 2001;30:683–95.
- [21] Arghode V, Gupta A. Development of high intensity CDC combustor for gas turbine engines. *Appl Energy* 2011.
- [22] Katsuki M, Hasegawa T. The science and technology of combustion in highly preheated air. *Symp Combust* 1998;27:3135–46.
- [23] Wünnig JA, Wünnig JG. Flameless oxidation to reduce thermal no-formation. *Prog Energy Combust Sci* 1997;23:81–94.
- [24] Choi G-M, Katsuki M. Advanced low NO_x combustion using highly preheated air. *Energy Convers Manage* 2001;42:639–52.
- [25] Galletti C, Parente A, Derudi M, Rota R, Tognotti L. Numerical and experimental analysis of NO emissions from a lab-scale burner fed with hydrogen-enriched fuels and operating in MILD combustion. *Int J Hydrogen Energy* 2009;34:8339–51.
- [26] Kawai K, Yoshikawa K, Kobayashi H, Tsai J-S, Matsuo M, Katsushima H. High temperature air combustion boiler for low BTU gas. *Energy Convers Manage* 2002;43:1563–70.
- [27] Gupta A, CHOMIAK J. Burner geometry effects on combustion and NO (x) emission characteristics using a variable geometry swirl combustor. *J Propuls* 1991.
- [28] Frassoldati A, Cuoci A, Faravelli T, Ranzi E, Astesiano D, Valenza M, et al. Experimental and modelling study of low-NO_x industrial burners. *MPT Metall Plant Technol Int* 2008;31:44–6.
- [29] Dally BB, Karpets AN, Barlow RS. Structure of turbulent non-premixed jet flames in a diluted hot coflow. *Proc Combust Inst* 2002;29:1147–54.
- [30] Dally B. Effect of fuel mixture on moderate and intense low oxygen dilution combustion. *Combust Flame* 2004;137:418–31.
- [31] Mancini M, Schwoppe P, Weber R, Orsino S. On mathematical modelling of flameless combustion. *Combust Flame* 2007;150:54–9.
- [32] Galletti C, Parente A, Tognotti L. Numerical and experimental investigation of a mild combustion burner. *Combust Flame* 2007;151:649–64.
- [33] Seepana S, Jayanti S. Flame structure and NO generation in oxy-fuel combustion at high pressures. *Energy Convers Manage* 2009;50:1116–23.
- [34] Cho E-S, Danon B, de Jong W, Roekaerts DJEM. Behavior of a 300 kWth regenerative multi-burner flameless oxidation furnace. *Appl Energy* 2011;88:4952–9.
- [35] Danon B, Cho E-S, de Jong W, Roekaerts DJEM. Numerical investigation of burner positioning effects in a multi-burner flameless combustion furnace. *Appl Therm Eng* 2011;31:3885–96.
- [36] Hosseini SE, Salehirad S, Wahid MA, Sies MM, Saat A. Effect of diluted and preheated oxidizer on the emission of methane flameless combustion. In: 4th Int. Meet. Adv. THERMOFLUIDS (IMAT 2011), vol. 1440, AIP Publishing; 2012. p. 1309–12.
- [37] Hosseini SE, Wahid MA, Abuelnuor AAA. High temperature air combustion: sustainable technology to low NO_x formation. *Int Rev Mech Eng* 2012;6(5):947–53.
- [38] Colorado AF, Herrera BA, Amell AA. Performance of a flameless combustion furnace using biogas and natural gas. *Bioresour Technol* 2010;101:2443–9.
- [39] Effuggi A, Gelosa D, Derudi M, Rota R. Mild combustion of methane-derived fuel mixtures: natural gas and biogas. *Combust Sci Technol* 2008;180:481–93.
- [40] Hosseini SE, Wahid MA, Abuelnuor AAA. Pollutant reduction and energy saving in industrial sectors by applying high temperature air combustion method. *Int Rev Mech Eng* 2012;6(7):1667–72.
- [41] Park PM, Cho HC, Shin HD. Unsteady thermal flow analysis in a heat regenerator with spherical particles. *Int J Energy Res* 2003;27:161–72.
- [42] Stanciu D, Isvoranu D, Marinescu M, Gogus Y. Second law analysis of diffusion flames. *Int J Thermodyn* 2001;4:1–18.
- [43] Nishida K, Takagi T, Kinoshita S. Analysis of entropy generation and exergy loss during combustion. *Proc Combust Inst* 2002;29:869–74.
- [44] Datta A. Entropy generation in a confined laminar diffusion flame. *Combust Sci Technol* 2000;159:39–56.
- [45] Hirschfelder JO, Curtiss CF, Bird RB. Molecular theory of gases and liquids. *Mol Theory Gases Liq*, by Hirschfelder Joseph Oakland, Curtiss Charles F, Bird R Byron, Wiley, New York [1964, c1954] Struct Matter Ser 1964. 1.
- [46] Hosseini SE, Wahid MA, Abuelnuor AAA. Biogas flameless combustion: a review. *Appl Mech Mater* 2013;388:273–9.

- [47] Ansys A. 14.0 Theory Guide. Fluent, Ansys, 140 Theory Guid Ansys Inc., 5 n.d.
- [48] Hosseini SE, Bagheri G, Wahid MA. Numerical investigation of biogas flameless combustion. *Energy Convers Manage* 2014;81:41–50.
- [49] Xiang JY, Cali M, Santarelli M. Calculation for physical and chemical exergy of flows in systems elaborating mixed-phase flows and a case study in an IRSOFC plant. *Int J Energy Res* 2004;28:101–15.
- [50] Anheden M, Svedberg G. Exergy analysis of chemical-looping combustion systems. *Energy Convers Manage* 1998;39:1967–80.
- [51] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical, and metallurgical processes. Hemisphere; 1988.
- [52] Bowman C. Kinetics of pollutant formation and destruction in combustion. *Prog Energy Combust Sci* 1975.
- [53] Hanson RK, Salimian S. Survey of Rate Constants in the N/H/O System. New York, NY: Springer, US; 1984.
- [54] Som SK, Datta A. Thermodynamic irreversibilities and exergy balance in combustion processes. *Prog Energy Combust Sci* 2008;34:351–76.
- [55] Westbrook CK, Dryer FL. Simplified reaction mechanisms for the oxidation of hydrocarbon fuels in flames. *Combust Sci Technol* 1981;27:31–43.